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Experimental Aspects of Ion Acceleration and Transport in the Earth's Magnetosphere

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1. INTRODUCTION

Ion acceleration processes are central to our understanding of the origins of all major particle populations within the Earth's magnetosphere. Although this fact has long been appreciated, only recently have we begun to become aware of the true complexity of these processes. This awareness has grown chiefly from experimental advances made over the past 10-15 years. It is my intent in this review to highlight areas where composition experiments have opened new doors of perception on magnetospheric phenomena that come loosely under the heading of ion acceleration.

By now many authors have emphasized that our improved knowledge of magnetospheric composition has lead to an overthrow of earlier concepts which centered on the solar wind as the origin of most hot plasma and trapped particles within the magnetosphere. Figure 1 shows the extent to which both ionospheric and solar wind plasma sources are now known to be interwoven. Qualitatively at least, one population feeds another in a cascade of particle and energy flow through the magnetosphere. The important questions now concern not so much the ultimate sources of ions as how one source region preconditions an ion population before passing it on to the next. It turns out that the preconditioning quite often depends on species specific processes, such as wave-particle interactions or charge exchange, that can greatly alter the signature of ion origins e.g. by enhancing or depleting one ion species relative to others.

While ion acceleration is the main topic of this review, it is important to keep in sight the overall dynamics of the magnetosphere. This involves the flow, not just of mass (represented by ions), but also of momentum and energy. For many years it was thought that all three quantities, mass, momentum and energy flowed almost exclusively from the solar wind to the terrestrial ionosphere via the magnetosphere. Now we know that a non-negligible mass flow takes place from the ionosphere back into the magnetosphere. We are beginning to learn that this transport may act as a kind of feedback on the magnetosphere and its processing of solar wind energy input. (Electrodynamic feedback is of course an old story in the magnetosphere.) Specific examples of ionospheric particle feedback include the role of oxygen ions in substorm initiation and of helium ions in mediating wave-particle interactions. Others may come to light in the future, perhaps in this volume.

This review is organized by dividing magnetospheric particles into five populations:

- plasmasphere (~ 1 eV)
- exo-plasmasphere (1 eV - 1 keV)
- plasma sheet (1-10 keV)
- ring current (10-300 keV)
- trapped radiation belts (> 300 keV)

The reader of course realizes that these populations are merely conveniences. They overlap both in space and energy: one man's plasma sheet is often another's ring current. Their usefulness is that "populations" convey to most of us a definite picture of a range of particle energies, densities, trajectories, etc. that are under discussion. Designating populations can also be used to picture a kind of order in an otherwise untidy magnetosphere (Figure 1).

One caveat, central to any discussion of magnetospheric ion measurements, cannot be sounded too loudly: magnetospheric ion abundances depend on solar cycle. This is well-established at 1 ~ 20 keV energies (Section 6) and is almost certainly the case at higher energies as well. Figure 2 therefore depicts the phasing of various magnetospheric missions with respect to the present solar cycle. Note that AMPTE, which is the first spacecraft to probe the bulk of the ion ring current, does so near solar minimum. A second, less important, caveat is that the author uses the terms heating and acceleration interchangeably when, strictly speaking, they aren't. Such semantic sloppiness is excused on the grounds that the two may often be indistinguishable to the observer and the reviewer can do no better.

If there is a single theme to this review, it is that composition plays a key role in magnetospheric dynamics. It is by now generally accepted that "heavy ions" can no longer be considered "tracer" particles. The occasion of this Chapman Conference provides an excellent opportunity to step back from our earlier pursuits and look afresh at a magnetosphere permeated by multispecies plasmas--and perhaps to reflect that the magnetospheres of Jupiter and other astrophysical objects are also not likely to be made up only of "protons". Magnetospheric acceleration processes which tend to select or enrich a particular ion species can also be expected to operate in astrophysical environments with as yet unforseen consequences.

In the sections that follow I give a brief instrumentation summary followed by one section devoted to each of the 5 populations listed above, with one final section for the ionospheric source region. In all sections I attempt to bring together some of the ideas and examples of ion acceleration in a discussion of the interplay between the ionospheric and solar wind source regions and the acceleration processes that take place between them.

2. INSTRUMENTATION

There is a need in the growing field of ion composition studies for a thorough and critical evaluation of experimental techniques. It is beyond the scope of this review to do more than scratch the surface of this neglected but important topic. An early review by Vasyliunas (1971) covers theoretical aspects of non-mass discriminating satellite-borne instruments. Wilken et al. (1982) and Balsiger (1982) have given useful overviews of mass analysis methods including magnetic analyzers, solid state detectors, and time-of-flight techniques. Energy analyzing laboratory instrumentation has been discussed more rigorously by Steckelmader (1973). What is still lacking, however, is a thorough examination of the critical tradeoffs among instrument parameters (energy range and resolution, angular range and resolution, mass range and resolution, geometric factor, signal to noise ratio, etc.) that largely determine performance. Questions often asked of experimenters include: 1) Can one determine 3-D velocity distributions for several ion species on times scales of a few seconds? 2) Why not?, and 3) Is this a limitation that will disappear as instrument technology advances? A more general issue to be considered is whether the field should invest precious resources in facility class instruments, following the lead of high energy physics and experimental astronomy. In order to sensibly discuss present day experimental results as well as future prospects, the field as a whole needs to be better informed. Such a review would at least remove some of the barriers to that discussion.

Table 1 provides a chronological sketch of instrument development in ion composition and the related area of ULF wave measurements. Particle instrumentation is divided into three energy regimes because different techniques tend to be applied in each range. The table includes a rough classification by instrument type as well as detectable mass to ionic charge ratio (M/Q) or nuclear charge (Z). Values of M/Q or Z included in the table are those that can be resolved as reported in the literature. The appropriate comparable data for waves is, roughly speaking, the frequency threshold. References are to instrumentation papers where available, or to "first results" papers where some abbreviated description of the experimental technique can be found. Of course it would be desirable to expand this table to include ranges and resolutions for the tradeoff parameters mentioned above, but that far exceeds the scope of this review. Rather the reader is asked to peruse Table 1 and note the accelerating development of composition instrumentation that has taken place over the last 2 decades. Several instrument pedigrees are evident in Table 1 (e.g., the OGO-5 magnetic spectrometer leading to RIMS on DE-1; GEOS-1 to CCE; 1069-25B to SCATHA; and IMP-7 to CCE) which shows that careful long-term development by a number of specializd groups was necessary to produce the current spate of composition results.

One rather subtle point that has had some impact on the course of magnetospheric physics was the early availability of composition measurements at very low (~ eV) and very high (~ MeV) energies. Both types of instrumentation were reasonably well developed in other areas of physics e.g. solid state detectors, gas proportional counters and such devices have their origins in low- to medium-energy nuclear physics. The energy range ~ 1 keV to ~ 100 keV has presented the greatest technical problems for composition measurements. These were solved only with technological advances such as rare earth magnetic materials, development of space-qualified very high voltage systems (~ 30-50 kV), and very thin-walled or thin surface barrier energetic particle detectors. Still newer developments such as position-sensitive particle detection should result in even greater advances in instrument capabilities, particularly in the area of time resolution.

3. THE PLASMASPHERE

The plasmasphere deserves attention in a review of acceleration processes for three reasons: first as a source of ions which may be accelerated in situ within the high altitude magnetosphere; secondly, as the background plasma that determines wave propagation and polarization characteristics; and thirdly, as the medium in which more energetic particles are embedded and to which they lose energy and momentum.

During the 1960's, limited composition measurements of the near-equatorial plasmasphere by the OGO-1,-3, and -5 mass spectrometers (Table 1) all found He^+/H^+ to be < 0.01 with negligible amounts of O^+ (Taylor et al., 1965; Harris et al., 1970). This picture of the plasmasphere changed with the advent of the GEOS-1, ISEE-1 and DE-1 mass spectrometers. The latter all yielded $He^+/H^+ \sim 0.1$ as a more typical value (Young et al., 1977; Waite et al., 1984; Horwitz et al., 1984) with excursions up to 50% He^+ by number. The reason for this discrepancy between OGO and later measurements need not detain us, but it now seems well established that the newer results are indeed correct (cf. Horwitz, 1982). Ion temperatures within the inner plasmasphere are $\sim$ 0.3 eV with a small radial gradient that leads to $\sim$ 1 eV near the plasmapause. Different ion species are in thermal equilibrium, as are electrons and ions. Rarer ion species are also present with He^{2+}, D^+, O^{2+}, N^{2+} and N^+ having been reported at levels of < 0.1%. Molecular ions (N_2^+, NO^+, O_2^+) have been seen out to 3 R_E over the polar cap during an intense storm (Craven et al., 1985) but have not yet been found within the plasmasphere.

In terms of identifying the sources of the more energetic ring current and radiation belt ions, the most important plasmasphere feature is its compositional ordering $H^+ > He^+ > O^+$ by density. This is in distinction to the composition of auroral beams and upwelling polar cap ions, in which $H^+ > O^+ > He^+$ is a clearly established feature. Although such an ordering is a useful guideline for identifying the source of particles at energies up to a few tens of keV, it should be kept in mind that the solar wind elemental ordering is also H>He>O and is therefore qualitatively similar to that of the plasmasphere. This is an important consideration at higher energies (> 0.1 MeV) where solid state detectors are the primary tool (used alone they distinguish only nuclear, not ionic, charge). At very high energies, trapped ions gain or lose electrons through collisions and thereby work toward a charge state equilibrium (cf. Spjeldvik and Fritz, 1978). Thus initial charge states alone do not necessarily serve as viable markers of ion origins and the plasmasphere elemental ordering could in principle be confused with that of the solar wind. Fortunately the present level of instrumentation offers another test of ion origin, the elemental C/O ratio. We return to this again in Section 7.

The outer plasmasphere and the region adjacent to it (the so-called "trough") provide fertile ground for the production of plasma waves through a variety of mechanisms (cf. Shawhan, 1979). Of particular interest here are ion cyclotron waves (ICWs) just above or below the local gyrofrequencies of the two dominant cold ion species: H^+ and He^+. It has long been known that the presence of a second ion species introduces new cutoffs and resonances into the plasma wave dispersion relation. Both propagation and polarization characteristics of ion cyclotron waves are therefore altered by the presence of He^+ or O^+ mixed in with the cold hydrogenic background plasma found within and outside the plasmasphere. One important consequence of this cold multi-species plasma is that ICWs observed in the equatorial region at L ~ 4-7 by GEOS and ATS-6 display propagation and polarization characteristics showing clear control by He^+ and O^+. The ICWs are generated by the pitch angle anisotropy of hot (20 ~ 50 keV) protons and then propagate away from the equator. Ray tracing simulations by Rauch and Roux (1982) show that the waves are reflected within ~ 20° of the equatorial plane and bounce back and forth between wave "mirror points", gaining amplification on each bounce. Amplification comes about because the presence of $\gtrsim$ 5% He^+ enhances the ICW growth rate (Roux et al., 1982) while the wave reflection occurs when the local ICW frequency matches the bi-ion hybrid frequency which is controlled again by the presence of cold He^+. The ICWs in turn act back on the cold He^+, and through a mechanism not yet clearly established (but possibly quasi-linear diffusion, Gendrin and Roux, 1980; or non-linear effects, Mauk et al., 1981; Roux et al., 1982), the waves strongly heat the He^+ ions transverse to the local magnetic field direction giving rise to a hot exo-plasmaspheric population (Section 4).

Aside from the GEOS-1 observations directly showing He^+ heating up to ~ 100 eV, there is good circumstantial evidence for wave heating of ions based on the prevalence of so-called "pancake" or trapped pitch angle distributions (i.e. peaked at 90°) of both H^+ and He^+ (Horwitz et al., 1981; Olsen, 1981) and the resonant absorption of ICWs at both He^+ (Mauk et al., 1981) and O^+ (Fraser and McPherron, 1982) equatorial gyrofrequencies. Horwitz et al. have also reported that trapped distributions occur preferentially in the dayside magnetosphere, which is the locus of ICW events and heated He^+ (Roux et al., 1982). These experimental results have instigated considerable theoretical work on gyroresonant wave-particle interactions and the interested reader is referred to reviews by Gendrin

(1983) and Roux (1985), as well as to work by Gomberoff and Neira (1983). For a different view on accelerating and trapping suprathermal ions see Curtis (1985). As Gendrin has pointed out, wave-particle interactions mediated by He^+ represent a kind of frictional interchange of energy between hot ions of one species (H^+) and cold ions of another (He^+) and extends as well to cold electrons (Roux et al., 1984).

In addition to wave-particle interactions, heating of the outer reaches of the plasmasphere may be a consequence of the filling of flux tubes from the ionosphere. The filling process is evident from flowing distributions of H^+ and He^+ (Sojka et al., 1983) and from the steady increase in cold isotropic plasma during periods of quieting magnetic activity (Horwitz et al., 1981, 1984). The outer or formational plasmasphere in these studies is found to be hotter (1-3 eV) than the inner core of the plasmasphere (0.5 eV), a feature already noted earlier (Serbu and Maier, 1970; Bezrukikh and Gringauz, 1976) and recently confirmed by Comfort et al. (1985) with DE-1.

Several of the studies cited above have addressed the problem of heating the outer plasmasphere. Serbu and Maier (1970) noted that hotter (~ 5 eV) ions have Coulomb collision lifetimes many times longer than their bounce times, whereas colder ions (~ 0.5 eV) could scatter and be lost over a bounce period. This process should be more effective in the dense inner plasmasphere than the outer, however, whereas the temperature gradient is in the opposite sense. Sojka et al. (1983) found that as DE-1 moved to higher L-shells, field-aligned flows of H^+ and He^+ ions changed from counterstreaming flows coming from both hemispheres, to unidirectional flows coming only from the nearest hemisphere. These observations are qualitatively in keeping with the interaction expected of counterstreaming polar wind ion beams near the equator. Such beams would be initially unstable to ion acoustic waves until sufficient density had built up at the equator (Schulz and Koons, 1972). Singh and Schunk (1983) find that suprathermal forerunner ions (~ 2.5 eV) may be initially unstable and start the process of scattering and thermalization. A colliding beam interaction has two important consequences: ion flow energy is converted to thermal energy, possibly accounting for higher temperatures in the outer plasmasphere; and the plasmasphere fills from the top (equator) down. The latter is an important consideration for wave propagation studies since it implies density and composition may vary in an unexpected manner along the field line.

4. THE EXO-PLASMASPHERE

As I have suggested elsewhere (Young 1983a, b) there is evidence for a suprathermal population roughly adjacent to the plasmapause, extending outward perhaps 1-2 R_E. While it could be argued that this is nothing more than the low-energy tail of the ring current or plasma sheet, the composition of the "exo-plasmasphere" is distinctly terrestrial in nature, but with a strong plasmaspheric flavor due to large He^+/H^+ and O^{++}/O^+ ratios. Typical ion energies run from ~ 10 eV (Gurnett and Frank, 1974; Horwitz et al., 1981; Sojka et al., 1983; Sojka and Wrenn, 1985) up to as high as ~ 1 keV (Balsiger et al., 1983). Pitch angle distributions range from trapped through conical (defined as flux maxima at pitch angles $0° < \alpha < 90°$ or $90° < \alpha < 180°$) to field-aligned (Singh et al., 1982). Among the more consistent features of this plasma is that He^+ moreso than H^+ tends toward trapped distributions suggestive of acceleration perpendicular to the local magnetic field. (Horwitz et al., 1981; Roux et al., 1982; Sojka et al., 1983). Olsen (1981) has found a strongly trapped (within a few degrees of the equator) population that may be predominantly plasmaspheric

H^+ (Quinn and Johnson, 1982). The O^+ exo-plasmaspheric component tends to be field-aligned and generally more energetic than the He^+, and is likely to be associated with direct O^+ injection and trapping from the ionosphere rather than a purely plasmaspheric source (see Section 8, also Young, 1979; Kaye et al., 1981a,b). Recent results from AMPTE/CCE are consistent with an exo-plasmaspheric source for He^+ and O^{2+} fluxes observed at the inner edge of the storm-time ring current (Shelley et al., 1985b).

A primary heat source for the outer plasmasphere is wave-particle interactions driven by the anisotropy of energetic protons as described in Section 3 for He^+. In addition to heating He^+ by this process, indirect evidence of WPI near F_{O+} also exists (Fraser and McPherron, 1982; Fraser 1982) although no observations of locally heated O^+ ions have been reported. Perpendicular heating of suprathermal (not cold) H^+ by ICWs above the hydrogen gyrofrequency may also take place. These waves are generated by unstable proton ring distributions (Perraut et al., 1982). In this case the hot, unstable protons give up energy to the lower energy (0.1-5 keV) part of the proton spectrum. In all instances of wave-particle interactions cited above, the source of proton pitch angle anisotropy is gradient and curvature drift of protons from near local midnight around to local noon. Thus the free energy for cold ion acceleration is supplied by substorm injection or, in some cases, simply ExB convection from the tail plasma sheet.

In this section we have tried to make a case for high altitude, near-equatorial acceleration of cold plasmasphere ions. It seems important to make this distinction because the composition of this population, which can act as a feeder for the ring current (Section 6), is different from that of directly injected auroral fluxes. For this exo-plasmasphere population the importance of He^+ stems from source composition rather than from the charge-exchange loss process which also favors high He^+ abundances (Section 6).

One last note on heating the exo-plasmasphere: It seems plausible that turbulence in the convective flow induced by the dawn-dusk electric field could also heat this region. Shear in the convective (ExB) flow pattern should occur preferentially at the plasmapause during periods of increasing or decreasing magnetic disturbance levels. Whether shears in the ExB convection pattern give rise to MHD turbulence remains to be seen, but if so then this is perhaps another source for ion heating.

5. THE PLASMA SHEET

No other region of the magnetosphere elicits as much controversy among experimentalists as does the magnetotail. The reasons for this seem to be its sheer vastness, and its dynamic, time-varying nature coupled with a lack of multiple spacecraft observations. All of which make certain classes of measurements by a single spacecraft problematic at best. For example, controversies over spatial vs. temporal effects (e.g. plasma sheet expansion vs. flapping to name but one) are legion. And yet the magnetotail and plasma sheet are central to magnetosphere dynamics as resevoirs for the storage of nearly all energy (in the form of magnetic flux and hot plasma) and mass consumed during the substorm process.

Build-up of magnetic flux in the tail followed by its release through reconnection is the generally agreed upon paradigm for substorms. Through this process ion acceleration to energies as high as ~ 1 MeV occurs. While it is of interest to know how these great energies come about, of greater importance to magnetosphere dynamics is the acceleration and earthward motion of the bulk of the plasma sheet particles. Acceleration is manifest through plasma flows both earthward and tailward at velocities up to hundreds of km/s during substorms; as plasmoids ejected from the tail, carrying with them substantial amounts of particle and field energy; and as energetic ions (1 keV ~ 1 MeV) accelerated along the boundary of the plasma sheet. All of these processes are touched on in this section, again with emphasis placed on composition aspects.

It is perhaps useful to point out that the ISEE-1 ion mass spectrometer (Table 1) is still the only mass resolving instrument measuring bulk plasma to penetrate the magnetotail region beyond ~ 7 R_E. ISEE-1 also carried non-mass-discriminating plasma analyzers (Eastman et al., 1984) and energetic particle instruments capable of distinguishing O^+ (Hovestadt et al., 1978). Energetic particle and plasma instruments on IMP 7 and 8 have measured characteristics of streaming magnetotail ions out to 45 R_E. Still further down tail (80-220 R_E) ISEE-3 has revealed the apparent solar wind character of energetic (6-150 keV/amu) ions found in plasmoids (Gloeckler et al., 1984).

In terms of particle storage times, the plasma sheet must be considered to be a temporary resevoir of magnetospheric plasma. Before the present era of heavy ions, the plasma sheet was thought to be fed by the solar wind via the high-and low-latitude boundary layers or by direct diffusion from the magnetosheath into the flanks of the magnetotail. Hill (1974) pointed out that a solar wind particle capture rate of only ~ 0.1% was needed to supply the quiet plasma sheet. By the same token, the polar wind flux (4 $10^8/cm^2 s$) could only supply ~50% of the estimated quiet time loss rate of 5 x 10^{25}/s from the plasma sheet. Hill discussed other evidence which, at that time, suggested a solar wind origin for the plasma sheet. As he pointed out, it made for a tidier theory if both mass and momentum transfer requirements for the plasma sheet could be met by a single source, the solar wind. The most recent ISEE-1 composition measurements in the tail (reviewed below) suggest that the solar wind is indeed the primary ion source during magnetically quiet times. During disturbed times, however, the plasma sheet seems to fill with a steady stream of ionospheric material.

Compilations of significant amounts of ISEE-1 plasma sheet composition data have been presented by Sharp et al. (1982) and Lennartsson and Shelley (1985). Their basic conclusions are that in magnetically quiet conditions, ions in the plasma sheet out to 23 R_E are ~ 98% of solar wind origin and have been accelerated to equal energy per nucleon with H^+ receiving slightly more energy than He^{2+}. The average He^{2+}/H^+ density ratio is 0.03, somewhat less than the typical (but not simultaneously measured) solar wind value of 0.04-0.05. As magnetic activity increases (Figure 3) the O^+/H^+ density ratio increases until, as Sharp et al. infer, plasma sheet ions are ~ 50% terrestrial in origin. At the same time, the amount of solar wind He^{2+} actually decreases inside 23 R_E (Lennartsson and Shelley, 1985). With increased magnetic activity, the average solar wind ion energy in the plasma sheet increases a factor of 2, but in such a way that H^+ gets relatively more energy than He^{2+} and the two species tend toward equal energy per charge rather than equal energy per nucleon. Interestingly, Lennartsson and Shelley report that at very low levels of activity, the mean ion energy approaches solar wind values (e.g. 1 keV for H^+ and 4 keV for He^{2+}). Their study, covering all ISEE-1 data in 1978 and 1979, shows a definite solar cycle correlation as the average O^+/H^+ ratio increased by a factor of 3-4 at all levels of magnetic activity.

More energetic ions (>20 keV) are also present within the plasma sheet proper, are found in plasmoids ejected by substorm activity from the distant tail, and appear as bursts of flowing ions seen on the boundary of the plasma sheet. Within the plasma sheet, these more energetic ions extend up to > 1 MeV and may appear as a distinctly non-thermal power law tail extending from the Maxwellian distribution of the main population (Sarris et al., 1981). More complex energetic ion distributions were found in a study with ISEE-1 (Ipavich and Scholer, 1983). Ipavich et al. (1984) also report that the energetic O^+ content of the plasma sheet (as measured by O^+/H^+) increases at least a factor of 10, up to $O^+/H^+ \sim 0.4$, with magnetic activity (determined by K_p), qualitatively similar to the Sharp et al. (1982) results.

Magnetic activity is also associated with beams of energetic ions flowing earthward, tailward, or simultaneously counterstreaming along the boundary of the tail plasma sheet (Krimigis and Sarris, 1979; Mobius et al., 1980; Williams, 1981; Lui et al., 1983). Such bursts have been recorded most frequently in association with crossings of the plasma sheet boundary layer, which seems to be a consequence of their association with substorm activity (Krimigis and Sarris, 1979). (Since the plasma sheet is known to thin and then expand with substorm phases, it seems most likely that the 10 ~ 50 km/s motion of the plasma sheet past a satellite is responsible for bringing the boundary layer into view during crossings, than is the relatively slow (1 ~ 2 km/s) motion of the satellite in inertial space. However Eastman et al. (1984) argue that the boundary layer persists even during magnetically quiet periods ($K_p = 0$) and is a permanent feature of the tail.) The composition of these energetic particles seems to be primarily solar wind, based on He^{2+}/H^+ ratios (Mobius et al., 1980) however Ipavich et al. (1985) report seeing energetic O^+ streaming tailward during two substorms on March 22, 1979 (CDAW 6 analysis).

As discussed by many of the above authors and summarized in Baker and

Fritz (1984), the origin of the energetic ion beams is now generally taken to be acceleration at one or more X-type neutral lines formed in the magnetotail during substorm activity at distances of 10 R_E to > 100 R_E tailwards from the Earth (Williams, 1981). Acceleration at the neutral line(s) proceeds by the current sheet mechanism proposed by Speiser (1965) and discussed by Lyons and Speiser (1982). Acceleration at a neutral line rather naturally leads to ion flows at the outer boundary of the plasma sheet. An important consequence of this acceleration process is discussed by Lyons and Evans (1984). Low altitude satellite data shows that precipitating electrons causing the discrete aurora are associated both temporally and spatially with energetic proton fluxes (30-800 keV) that resemble energetic proton distributions seen in the high latitude boundary of the plasma sheet. The observed proton flux spectra are in agreement with characteristics computed for neutral sheet acceleration, the implication being that discrete aurora often occur on field lines that map along the boundary layer and are connected to regions of current sheet acceleration.

At ion energies below 1 keV, Eastman et al. (1984) have argued that this same plasma sheet boundary layer is the conduit for upflowing ion events originating in the auroral zone, and that the streaming ions eventually evolve through pitch angle scattering to populate the central plasma sheet. Evidence for scattering of upward accelerated field-aligned ions as a means of populating the plasma sheet has been advanced by Ghielmetti et al. (1979). They noted the predominance of upward flowing over downward flowing ions at low altitudes (< 8000 km) on magnetic field lines connecting to the low latitude boundary of the auroral zone and to the inner plasma sheet. Because downward flowing ions were observed in association with enhanced fluxes of trapped ions, Ghielmetti et al. argued, based on spatial location and relative phase space densities, that both populations could have originated from the more commonly observed upward flowing ions. Thus the S3-3 observations show evidence for ion injection over a wide range of latitudes into the central plasma sheet without the ions necessarily passing through the plasma sheet boundary layer. F-urthermore, upward flowing auroral ions are generally associated with inverted-V events or occasionally occur over very wide latitudinal extent (Sharp et al., 1979; Lundin et al., 1982; Quinn and Johnson, 1985; Shelley, 1985). ExB drifts and dispersion of the upward flowing ions (particularly O^+) would in any case cause the beams to be injected throughout the main body of the plasma sheet, as observed by Sharp et al. (1982). These observations seem to imply injection throughout the plasma sheet and not just in the boundary layer as Eastman et al. have suggested.

The picture which emerges is that at low levels of magnetic activity the solar wind populates the bulk of the plasma sheet (at least out to 23 R_E) with little additional ion acceleration. Substorm activity leads to the upward acceleration of auroral ions and scattering into the plasma sheet together with the formation of neutral line(s) and earthward acceleration of energetic ions. Increased convection in the lobes together with increased reconnection in the tail should increase the amount of solar wind ions found in the plasma sheet, but apparently does not. This may be a consequence of tailward movement of the reconnecting region. Energetic ions are observed at low altitudes in conjunction with discrete auroral forms, and at high altitudes as beams on the plasma sheet boundary. Counterstreaming comes about as earthward directed ions mirror and return to the spacecraft (Williams, 1981). As magnetic activity increases, the flux of accelerated particles out of the auroral zone increases and the plasma sheet fills with ionospheric material that may alter its response to subsequent substorms (Baker et al., 1982).

Shelley (1985) estimated that the relatively small terrestrial component of the quiet time plasma sheet (~ 2%) can be easily supplied by either quiet time upward flowing auroral ions (Collin et al., 1984) or by accelerated polar cap ion outflows observed on DE-1 (Yau et al., 1984). During magnetic storms (Dst ~ -100 γ) the outflow of both O^+ and H^+ increases significantly and the auroral acceleration region alone is sufficient to supply the observed terrestrial content of the plasma sheet. Other transport channels (magnetotail lobe streams and magnetopause boundary layers) may, in Shelley's estimation, contribute significantly, but are not likely to be the primary source of the storm-time plasma sheet.

One final note on changes in plasma sheet composition with magnetic activity is the observation that the absolute density of He^{2+} decreases with increasing activity (Lennartsson and Shelley, 1985). One might speculate that this comes about because He^{2+} is preferentially denied access to the plasma sheet inside 23 R_E as a result of changing convection and/or acceleration patterns within the magnetotail. Increased convection might, for example, cause He^{2+} entering via the magnetopause boundary layer to be carried further downtail before it could gain access to the plasma sheet. Tailward motion of the reconnection region in the plasma sheet could have a similar effect, as would changes in the pattern of disruption of the tail current system which feeds the ionospheric Birkelund currents (Lennartsson and Shelley, 1985; Baker et al., 1982). Baker et al. (1982) have suggested that the presence of O^+ in the near-Earth plasma sheet may define regions in which ion tearing mode growth rates are increased and the threshold for instability leading to substorm onset is lowered. More recent data on the distribution of O^+ densities in the tail (Lennartsson and Shelley, 1985) are consistent with dawn-dusk asymmetries noted by Baker et al.

6. THE RING CURRENT

Without a doubt one of the most exciting experimental results in recent annals of magnetospheric physics has been the long awaited measurements by the AMPTE/CCE experiments of the composition of the terrestrial ring current. Ring current studies were formerly plagued by our inability to measure the composition of ions in the energy range 20-300 keV, wherein lies ~ 90% of the ring current energy density (Williams, 1980, 1983). Initial CCE results reported in the literature are limited to a single main phase magnetic storm, that of September 4-6, 1984 (Williams and Sugiura, 1985), however more extensive data are included in the present volume.

Like the plasma sheet, the Earth's ring current is a storehouse of accelerated magnetospheric particles and hence of energy. Particles in the ring current are stored by virtue of trapping in the more dipolar regions of the geomagnetic field. Because they may execute many circuits of the Earth, storage times are much longer than in the plasma sheet (days vs. hours) and this leads to their energization through radial (cross L-shell) diffusion. Particles are lost from the ring current either through charge exchange with neutral hydrogen, or through pitch angle scattering into the atmosphere. The sources and pathways for ion entry into the ring current are better understood as the result of CCE and earlier composition measurements, but questions remain.

The first direct measurements of ions ("protons") and electrons below ~ 50 keV in the ring current were reported by Frank (1967) and later extended to ~ 1 MeV by Smith and Hoffman (1973). As discussed by Lyons (1984), these and other non-composition data showed that the particle flux increases occurring during magnetic storms contributed to the main phase ring current primarily inside of L=4. Flux increases outside this altitude are no greater during main phase storms than during substorms. The inner edge of the ring current largely coincides with the plasmapause as noted by Frank (1971). This was predicted on theoretical grounds as the consequence of pitch angle diffusion driven by ion cyclotron wave-particle interactions (Cornwall et al., 1970). There is general agreement, however, that the primary loss mechanism for ring current ions is charge exchange with geocoronal neutral hydrogen rather than wave-particle induced pitch angle scattering. It should be kept in mind that both of these loss mechanisms are composition dependent, and, indeed, that they may be coupled through the mechanism of charge exchange-induced anisotropies in the hot ion pitch angle distributions (Solomon and Picon, 1981).

The geostationary orbit ($L \simeq 6.6$) lies at the outer boundary of the quiet time ring current, in the general region where strong plasma injections are observed in the dusk to midnight local time sector. McIlwain (1972, 1974) has used ATS-5 plasma data to demonstrate that this region is literally a gateway for the passage of kilovolt plasma from the tail plasma sheet and the ionosphere (Mauk and McIlwain, 1975) into the inner magnetosphere. Injection, drift and dispersiion of ionospheric material in this region has been described by Kaye et al. (1981b) and Strangeway and Johnson (1984) using S3-3 and SCATHA data. Particles injected near L = 6.6 are on trapped orbits under most conditions of magnetic activity, and from there begin to convect or diffuse inward into the ring current and radiation belts.

Using data from the GEOS-1 and -2 ion mass spectrometer, Young et al. (1982) showed that there was a strong solar cycle dependence in the number density of the terrestrial ions He^+ and O^+ at energies of 1-15 keV (Figure

4). Similar long term trends attributable to the solar cycle have been found in ISEE-1 composition data from the tail plasma sheet between 10 and 23 R_E (Lennartsson and Shelley, 1985) and in upflowing ion events observed with DE-1 (Yau et al., 1985) and S3-3 (A. Ghielmetti, private communication, 1984).

In retrospect, the ionospheric origin of keV magnetospheric ions should have lead one to expect that some form of solar cycle dependence would be observable. Responses of the upper atmosphere and F-region ionosphere to solar cycle variations in the solar EUV output are well known (cf. White, 1977). Young et al. (1982) argued that increases in solar EUV (as quantified by $F_{10.7}$, the 10.7 cm radio flux index) would increase the production rate of ionospheric species, but more importantly would raise the scale heights of both ions and neutrals. Because of its greater mass, the scale height of O^+ would be affected the most and that of H^+ the least, with He^+ falling somewhere in between. This in fact is what is observed on GEOS in terms of ion density correlations with $F_{10.7}$. Lockwood (1984) has examined the question of solar cycle control of the auroral O^+ acceleration process in some detail. He used as a hypothesis that the topside ionosphere is unstable to ion cyclotron waves and that O^+ seen in upward flowing ions is heated initially by these waves. Lockwood showed that the escape of O^+ depends critically on its initial acceleration to an energy of ~10 eV, above which it overcomes the charge exchange and Coulomb collision barriers presented by neutral hydrogen and oxygen atoms. Some contradiction between Lockwood's results and the GEOS observations arises because the O^+ escape flux should be highest at low topside ion densities whereas the reverse seems to be true for the observed solar cycle effect. In any case, this type of study is badly needed to sort out the competing effects of ionospheric chemistry, ion transport, and the plasma physical problem of ion acceleration.

Moving on to higher energies, in the absence of direct measurements of ring current composition in the critical 20 keV–300 keV range, a number of studies were undertaken in order to infer indirectly the ring current composition during the storm recovery phase. These were based on deducing the characteristic time scales for ring current decay (Tinsley, 1976; Lyons and Evans, 1976; Smith et al., 1981). Observed decay rates of 1–3 days in the storm-time Dst index were far too slow to be accounted for by H^+ lifetimes against charge exchange, leading to the suggestion that He^+ or O^+ should be the dominant ring current ion at energies below ~ 50 keV. This surmise was confirmed below ~ 20 keV by GEOS-1, ISEE-1 and PROGNOZ-7 data, and seems to be consistent with limited CCE results (Krimigis et al., 1985).

Published data from the AMPTE/CCE composition instruments are thusfar limited to a single storm in September, 1984. The CCE is in a 15.7 hr. orbit with apogee near 1300 LT and 8.8 R_E. The ring current that developed during the September storm was fairly intense (preliminary D_{st} = -120 γ) but asymmetric (Williams and Sugiura, 1985). During the storm initial phase (Sept. 4) K_p reached 7o and 8-, on Sept. 5 it reached 7o.

Figure 5 is a summary plot of ion energy density during the storm main phase when the CCE was inbound near local dusk. Prior to the storm the quiet time ring current energy density was dominated by H^+ with peak density at 100 to 300 keV. During the storm main phase, O^+ fluxes increased most dramatically at energies $\lessdot$ 300 keV together with appreciable increases in H^+ and He^+. Gloeckler et al. (1985a) note that H^+, He^+, He^{2+} and O^+ spectra are all relatively similar below 300 keV/e with peaks at ~ 15 keV/e and ~ 150 keV/e. There is no obvious difference between energy spectra for ions of terrestrial origin (O^+, He^+) vs. those of solar wind origin (He^{2+}, $[CNO]^{5+}$) when plotted at equal E/Q, suggesting primarily E/Q dependent acceleration. At energies < 17 keV Shelley and co-workers find that the H^+ and O^+ pitch angle distributions, however, show significant differences, with the latter exhibiting evolution from isotropic toward trapped characteristics, and the former evolving from field aligned toward trapped distributions.

The relative abundances of solar wind ions below 300 keV/e observed within the ring current (He^{2+}, $[CNO]^{5+}$, $Si^{>4+}$, and $Fe^{>9+}$) are remarkably similar to their solar wind values, suggesting little mass or charge discrimination effects in solar wind ion entry (Gloeckler et al., 1985a). One further note is that an integrated oxygen charge state spectrum for 1-300 keV/e taken over L = 8.6 to 2.3 shows that although charge exchange processes are at work creating O^{3+}, O^{4+} and O^{5+}, the solar wind and ionospheric sources are clearly delineated. During the storm recovery phase, O^+ above ~ 20 keV decays rapidly and an important question is whether it in fact feeds the higher charge states as suggested by Spjeldvik and Fritz (1978).

Acceleration and injection of ring current ions is known to occur through several pathways, although the relative contribution and time-dependence of each remains to be elucidated. Following Williams (1983), I list four "subliminally popular" generation mechanisms for the ring current and add two more that are suggested by recent observations and theoretical work. These pathways and related acceleration processes are depicted schematically in Figure 6.

1. <u>Earthward E x B drift of plasma sheet ions driven by the cross-tail convection electric field</u>. Acceleration occurs through μ and J conservation, with the side effect that initially isotropic particle distributions become anisotropic and are therefore potentially unstable to elec-

tromagnetic ion cyclotron waves (Kaye et al., 1979). The Rice model (Wolf et al., 1982) simulates formation of the ring current magnitude (Dst) quite well by the convection process, although the ring current location at the inner edge of the plasma sheet (L ~ 5) is not in agreement with the observed inner edge at L ~ 3.

2. Upward accelerated auroral ions. The particle source is the topside ionosphere and hence tends to be rich in O^+. Acceleration is found to occur primarily parallel to the magnetic field followed by isotropization near the equatorial plane. These ions populate both the near and distant plasma sheet (Section 5). Pitch angle diffusion toward trapped distributions is an important intermediate step in populating the ring current by this mechanism. Evidence for pitch angle scattering has been obtained most recently from CCE (Shelley et al., 1985b), from SCATHA observations of near-equatorial beams (Richardson et al., 1981) as well as the work of Ghielmetti et al. (1978).

3. In situ acceleration at the substorm injection boundary, first proposed by McIlwain (1974). Subsequent work on this model by Moore et al. (1981) has led to the suggestion that the impulsive, dispersionless nature of the substorm injection process is caused by an earthward propagating compressional wave set loose by the collapse of magnetotail field lines at the onset of rapid reconnection in the tail (cf. Baker et al., 1979). The induced electric field associated with this rapid magnetic field change is responsible both for injecting and heating plasma sheet particles. Moreover, Quinn and Johnson (1985) have identified the injection boundary with intense beams from the ionosphere which are similar to the field-aligned component of "zipper" events. This process has been observed only on the outer ($L > 6$) ring current regions. Presumably it would move earthward with the equatorward expansion of auroral lactivity during main

phase storms. In any case, the injected populations serve as the feeder for other processes (see below) that further accelerate ions.

4. Earthward adiabatic transport of a pre-existing trapped particle population (Lyons and Williams, 1980). Tests of this hypothesis with Explorer 45 data showed that pre-storm distributions of ions and electrons could reproduce storm-time distributions quite well under the assumption that an azimuthal equatorial electric field of 0.3 ~ 1.0 mV/m acts over an appreciable (90° ~ 270°) range of drift longitudes. The new CCE data set offers an excellent opportunity to repeat this experiment, particularly since apogee is well beyond the expected injection boundary.

5. Direct injection of magnetosheath plasma into the outer ring current during main phase storms. Injection may be into the dayside boundary layer plasma (Lundin et al., 1982) from which ions can in principle drift into the outer ring current. PROGNOZ-7 observations suggest that impulsive solar wind injections occur in a manner remarkably like the model proposed by Lemaire (1977) and Heikkila (1979). Intruded solar wind plasma seems to be necessary in order to explain the so-called "mixed regions" containing hot, non-flowing solar wind enriched plasma observed preferentially in the dawn-side magnetosphere by GEOS (Balsiger et al., 1980) and ISEE-1 (Lennartsson et al., 1981).

6. Field-aligned injection of ions from the tail neutral sheet. As discussed in Section 5, bursts of field aligned energetic ions (1 keV to > 1 MeV) in the plasma sheet boundary layer result from reconnection and acceleration in the tail neutral sheet. Some of these ions (and electrons) are able to reach the auroral zone (Lyons and Evans, 1982) but in addition can also populate the main plasma sheet (Sarris et al. 1981) through the angular divergence inherent in the acceleration process, as well as through E x B convection and scattering. Injection of energetic ions directly into

the outer ring current occurs during substorms (Baker et al., 1979) and there is no reason why they could not contribute as well to main phase storms. Since these ions are seen at 6.6 R_E it is likely that they are also injected even deeper into the ring current by the same process, namely large scale induction electric fields.

In summary, we have identified at least six mechanisms by which the injection of ions into the inner or outer ring current has been observed to occur. As a number of authors have noted, it is unlikely that only one process is dominant; it is certainly conceivable that all processes are in part responsible for ring current generation. The task is then to study each in systematic fashion and particularly to understand how the contribution from each varies with storm phase and from storm to storm. Since some processes favor injection of a more solar wind-like component (5,6), others a pure terrestrial component (2), or still others a mixture of the two in variable proportions (1,3,4) it seems likely that the composition of the ring current can vary with the relative contribution of each injection mechanism. Of course changes in the source populations feeding each injection channel are known to occur (e.g. the solar cycle effect on O^+) and will further complicate this picture.

7. RADIATION BELT

For ions the locus of the radiation belt extends from the limit of stable trapping ($L \approx 5$ on the long term) down to $L \approx 1.1$ where losses to collisions with the atmospohere can no longer be supported. The most energetic ions (> 100 MeV) are likely to be protons originating from the cosmic ray production of neutrons in the atmosphere and their subsequent decay (CRAND). Below this energy, ions originate at the outer boundary of the magnetospheric trapping region ($L > 5$). Acceleration up to radiation belt energies occurs through the process of radial diffusion driven by fluctuations in the large scale magnetospheric electric and magnetic fields which violate the third adiabatic invariant. Since the source of these large scale fluctuations and of the convection electric field is the solar wind, either through compressions of the magnetopause boundary (magnetic fluctuations) or through variations in the convection field, it is again the solar wind that is the ultimate energy source for ion acceleration. Once again, one of the big issues of radiation belt physics has been the origin of the trapped ions.

Somewhat surprisingly, at these very high energies instrumentation has proved adequate to the requirements for composition measurements. For example, a single key measurement is that the radiation belt C/O elemental abundance is > 0.5 (Hovestadt et al., 1978), a characteristic of only the solar wind since the ionospheric C/O ratio is $< 10^{-5}$ (Blake, 1973). There exist sufficient heavy ion measurements such that both the origin and the relevant physical processes in the radiation belt are relatively well understood. Excellent reviews of radiation belt physics have been given in recent years by Schulz and Lanzerotti (1974), Schulz (1975), Spjeldvik (1981) and Spjeldvik and Fritz (1983).

At first, measurements of heavy ($Z \geq 2$) ions were made only at low altitudes. These showed He and CNO fluxes to be a factor $\sim 10^2$ less than expected relative to known solar wind abundances. The problem turned out to be the very steep ion pitch angle distributions that are strongly peaked at 90°. Inner zone ($L < 2$) ion fluxes were found to fit a $\sin^n \alpha$ function with $n \approx 8$ for hydrogen and $n \approx 12$ for He (Blake et al., 1973). Similarly, in the outer zone ($L \approx 3$–5) $n \approx 5$ for hydrogen, $n \approx 8$ for He (Fritz and Williams, 1973; Hovestadt et al., 1981) and $n \approx 16$ for C and O (Hovestadt et al., 1981). These data refer to ion energies of ≈ 0.5 MeV/nucleon. The origin of steep pitch angle distributions is ascribed to the steepness of the ion energy distributions in the source region e.g. in the plasma sheet. Ions which conserve μ and J while diffusing inward will gain most energy near 90° pitch angles and least near 0°. Thus a very steep initial energy distribution such as that found in the plasma sheet will contribute energetic particles primarily near 90 pitch angles. Moreover, charge exchange and Coulomb energy loss will be greatest for small equatorial pitch angles (at least at total energies up to a few MeV) and these ions will be preferentially lost. Thus some of the differences between heavy ions and protons in the steepness of their pitch angle spectra at equal ion velocity (i.e. at equal energy per nucleon) may well be accounted for by differences in energy spectra within the source region.

Cornwall (1972) and Schulz (1975) suggested that if He^{2+} has less than four times the temperature (mean energy) of H^+ in the source region (plasma sheet) this would lead to a steeper He^{2+} than H^+ energy/nucleon spectrum and thence to the observed species dependent pitch angle distributions. Recent ISEE-1 data (Lennartsson and Shelley, 1985) show, however, that $E_{He}{}^{2+} = 4\, E_H{}^{+}$ to within ≈ 15% for all levels of magnetic activity except the highest, where equal ion energy per charge is more likely. The only CNO charge state measurements in the outer magnetosphere (L ≈ 6-7) which address this issue are those of AMPTE (Gloeckler et al., 1985a). These data show that during a single storm the $[CNO]^{2+3}$ average energy per charge was qualitatively similar for all ions including terrestrial species. The He^{2+} and CNO group average energy per nucleon was only about 1/2 that of H^+. Thus if storm or disturbed-time injections and subsequent rapid diffusion are a major contributor to the radiation belts, as seems likely, then the steep pitch angle distributions at L<5 can be understood in terms of the AMPTE/CCE data at L ≈ 6. The average ISEE-1 data from 10 to 23 R_E are in rough agreement for high levels of magnetic activity (storms) but not for low.

As mentioned earlier, composition of the radiation belts for $Z \geq 2$ ions measured near the equatorial plane at L ≈ 2.5-4 strongly indicates a solar wind origin, at least at energies of 0.4-1.5 MeV/nucleon (Hovestadt et al., 1978, 1981). The ISEE-1 data also show that Ne, Si, Mg are present at energies < 0.6 MeV/nucleon. Ions with higher rigidities apparently cannot be stably trapped due to violation of the Alfven criterion. The latter requires that the ion gyroradius be small (<.05) relative to $|\nabla B|/B$. Further evidence for the effect of this trapping criteria comes from the observed C/O ratio of 1 ~ 4 at energies of 0.45 to 1.3 MeV/nucleon at L ≈ 2.5-4. Since solar wind C/O values are ≈ 0.5, this enrichment of C relative to O can be understood from the fact that the O^{6+} ion has a sufficiently large gyroradius to violate the Alfven criterion outside L ≈ 3.5, where as C^{6+} does not (Hovestadt et al., 1978).

Observations now show considerable O^+ in the outer magnetosphere and ring current at energies of 1 ~ 300 keV, and one might ask what becomes of oxygen in the radiation belts where C/O ~ 1 precludes a terrestrial source. One answer is clearly that rapid charge exchange helps to dispose of O^+. Furthermore, the injected O^+ spectrum (at equal E/A) is simply too soft and/or too field-aligned to promote very many ions into the MeV range through radial diffusion. A third important effect, noted by Cornwall (1972), is that radial diffusion driven by electric fluctuations is proportional to ion $(Q/M)^2$, hence terrestrial O^+ and O^{2+} would diffuse far slower than O^{6+} and would thereby be diminished relative to higher charge states before much acceleration occurred. Given these three loss mechanisms for O^+ it is interesting that AMPTE/CCE results show that O^+

fluxes at 300 keV/e are ~ 10^3 more intense than $[CNO]^{\geq 3+}$ fluxes (Gloeckler, et al. 1985a). This indicates that despite losses, O^+ is energized and injected rapidly enough at least down to L = 3.7 to overcome its disadvantages relative to solar wind O^{6+}.

Explorer 45 data have yielded considerable detail on the storm-time injection and subsequent decay of radiation belt ions (see review by Spjeldvik and Fritz, 1983). By studying a series of storms in 1972, Fritz and Spjeldvik have found, in addition to large variability from storm to storm, that rapid injection of MeV ions (1 ~ 20 MeV depending on mass) can occur down to L ≈ 2.5 during a large storm. Largest enhancements occurred at the smallest L values and were far stronger for heavier than for lighter ions. Conversely, the heavier ion fluxes decayed more quickly than did the lighter ions. Decay periods were consistent with charge exchange and Coulomb losses nearer the Earth (L < 3.5) and with radial diffusion farther out.

In summary, it is generally considered that the principles of radiation belt theory are well understood. Nothing in the recent experimental results would contradict such a statement, however non-steady-state conditions during rapid injection of storm-time particles are still poorly elucidated. AS this brief review demonstrates, within the radiation belt a number of mass or species dependent effects are known to be important. Chief among these are:

- species and origin (terrestrial or solar wind) dependent energy spectra and pitch angle spectra occur in the radiation belt source regions,
- species dependent trapping takes place for high vs. low rigidity ions,
- species dependent radial diffusion results from electric (but not

magnetic) fluctuations (Cornwall, 1972), and

- loss processes are virtually entirely species dependent (charge exchange, Coulomb collisions, resonant wave-particle interactions).

8. IONOSPHERIC ACCELERATION PROCESSES

Mass spectrometers on S3-3 made the first observations of upward acceleration of kilovolt H^+ and O^+ ions over the auroral zones (Shelley et al., 1976). This was quickly followed by the identification of conical, rather than exclusively field aligned, ion distributions that imply a strong acceleration process acting transverse to the magnetic field (Sharp et al., 1977). There is also evidence for ion (and electron) acceleration through magnetic field aligned electric potential drops associated largely with "inverted V" structures (Mizera and Fennell, 1977; Hultqvist and Borg, 1978; Sharp et al., 1979; Collin et al., 1981; Klumpar et al., 1984). Acceleration via field aligned potential drops seems to be well understood, however the jury is still out on the nature of the transverse acceleration process. Evidence has been presented in a few studies that transverse and field aligned acceleration processes are related in a causative sense (Klumpar et al., 1984; Heelis et al., 1984; Kintner et al., 1979). Statistical studies, on the other hand, have tended to show that field aligned beams and conics (conics are the high altitude manifestation of transversely accelerated ions due to the action of the mirror force and conservation of μ) have different spatial distributions (Ghielmetti et al., 1978; Gorney et al., 1979) and therefore are not necessarily the product of the same underlying phenomena. Of course transverse acceleration at low altitudes produces parallel acceleration through the action of the mirror force, but the real question is whether regions of transverse acceleration are intimately related to field aligned potential drops and, ultimately, to the auroral process itself. Observations of transverse ion heating within regions of field aligned currents, of intense ion cyclotron wave activity, and of electrostatic shocks (Heelis et al., 1984; Mizera et al., 1981) all reinforce the consensus that this is indeed the case. Moreover there are ample candidate mechanisms for transverse acceleration—the question is which one(s) does nature choose.

Observations at low altitudes (~ 1500 km) typically show that upward accelerated ions are often seen in association with intense fluxes of precipitating electrons (not all studies have had access to magnetometer data hence the electron fluxes are taken as an indicator of field aligned currents) and occur in regions of low ambient plasma density (Klumpar, 1979). Theoretical studies have suggested that the agent for transverse acceleration is electrostatic hydrogen cyclotron waves. These take their free energy from drifting ionosopheric electrons moving either down (Ungstrup et al., 1979) or up (Dusenbery and Lyons, 1981) the auroral field lines. Simulations in which cold drifting electrons provide the free energy have shown that oxygen cyclotron waves should also become unstable and preferentially heat O^+ transverse to the magnetic field (Ashour-Abdalla et al., 1981). Unfortunately, oxygen cyclotron waves have not yet been reported and are inherently more difficult to observe than hydrogen waves.

At still lower altitudes (< 1000 km) the total observed ion acceleration is rather small although this really must be judged in terms of the roughly 100-fold gain over initial ionospheric temperatures. As a number of authors have noted, one problem with wave acceleration is that the heated ions are soon moved out of the acceleration region by the mirror force, thereby limiting their energy gain. This seems to e particularly true at low altitudes where conical distributions are very low energy (see below).

At higher altitudes (> 5000 km) intense waves are found frequently in association with more energetic transverse ion heating (Kintner et al., 1979). Localized regions of abrupt reversals and enhancements in the transverse auroral electric field have been termed electrostatic shocks (Mozer et al., 1977). They tend to occur at altitudes of 1 R_E out to a few R_E, are generally embedded in "inverted V" structures, and are associated with upward accelerated ions and electrostatic ion cyclotron waves. Borovsky (1984) has made a case for transverse ion acceleration in oblique (to the magnetic field) double layers. This can produce a number of the observed ion acceleration signatures and would resemble the electric field signatures of electrostatic shocks. Acceleration in oblique double layers can in principle provide a large amount of transverse energy necessary, for instance, to fulfill the observational requirements of Collin et al. (1981). The latter find that kilovolt upflowing oxygen is on the average about twice as energetic as H^+ and that about half of its total energy must have come from acceleration perpendicular to the magnetic field.

A related subject that has received much attention of late is ion "upwelling", primarily of O^+, at energies <100 eV and often <10 eV observed at high latitudes over the polar cap (Shelley et al., 1981; Gurgiolo and Burch, 1982; Waite et al., 1984) and at the boundary between polar cusp and polar cap (Lockwood et al., 1985). Although it might be thought that these ions are an high energy tail on the classical polar wind, it now appears that they are heated by transverse acceleration processes similar to those outlined above. In this case heating is inferred to take place at altitudes <u>below</u> where the charge exchange of O^+ with neutral hydrogen is important otherwise the observed upflow of O^+ could not take place at the flux levels measured. As discussed by Moore (1980, 1984) the neutral hydrogen exosphere represents a barrier to O^+ escape unless the O^+ is first accelerated to energies ~ 10 eV. At this point its cross section for charge exchange decreases sufficiently for ion escape to occur. Lockwood (1984) has made a thorough examination of this mechanism including elastic scattering, and has showed that acceleration to ~ 10 eV is sufficient for both H^+ and O^+ to escape the ionosphere from an altitude of 600 km.

Analysis of the stabilitly of upwelling ions and other injected ionospheric populations would be of interest in order to ascertain under what circumstances streaming ions would generate waves that lead to self-trapping. in any case, ion upflow and subsequent trapping now appears to be a widespread process that provides a pathway for energy transfer from the ionosphere to the equatorial magnetosphere. this process converts parallel flow energy, via wave-particle interactions, into perpendicular thermal energy. thus the upflow and subsequent trapping of ions represents momentum and energy as well as mass transfer from ionosphere to equatorial magnetosphere rather than the other way around, which is the more conventional picture. a quite similar energy pathway can be found in the injection of more energetic auroral ions into the plasma sheet (Section 5).

In summary, the observations seem to allow for the existence of several related acceleration mechanisms and quite possibly more than one may be found along a given auroral field line. While details may vary, all observations and theories have in common field aligned currents (whether up or down) as the causative agent. Current or drift driven instabilities generate waves which transversely accelerate the observed ions. Subsequent acceleration by parallel electric fields or further acceleration by waves may occur. None of the proposed mechanisms make outrageous demands on free energy sources and all reproduce some aspect of this very rich acceleration phenomena. This places stringent requirements on future experiments if one is to sort out the different acceleration mechanisms that are proposed.

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FIGURE CAPTIONS

1. Schematic relationship of magnetospheric particle populations. The ionosphere and magnetosheath are shown as both sources (top) and sinks (bottom) of particles. Approximate latitude of ionospoheric sources and sinks are shown schematically (e.g. flow into the plasmasphere is from near-equatorial regions, flow into the tail lobes is polar in origin). From this diagram it can be seen that virtually all latitudes feed magnetospheric particle populations, and also act as particle sinks. Characteristic ion energy increases from top to bottom in the figure (scale at left) as does, roughly speaking, the lifetime of trapped populations. (Figure updated from Young, 1983b).

2. Operational periods of magnetospheric spacecraft carrying ion composition experiments shown relative to the present solar cycle (using 13-month smoothed sunspot numbers, R_z). Dashed lines indicate extended (usually intermittent) or expected extension to present missions. Note that no polar spacecraft was operational for $\approx$ 2.3 years around the solar maximum period. (Adapted from Shelley, 1985.)

3. Average ISEE-1 plasma sheet composition during 1978-1979 from 10-23 R_E in energy range 0.1-16 keV/e (from Lennartsson and Shelley, 1985).

4. Average O^+ density in the energy range 0.9-15.9 keV obtained near L = 6.6 by GEOS-1 and -2. Data cover the rising phase and most of the maximum of the current solar cycle (from Young et al., 1982).

5. AMPTE/CCE ring current composition during the magnetic storm of Sept. 4-7, 1984. Energy density is integral over ~ 10 eV to ~ 5 MeV (from Krimigis et al., 1985).

6. Pathways for injection and acceleration of ring current ions. Dashed line represents a rough boundary between outer (quiescent) and inner (storm) ring current positions. Note that trapping of ionospheric source populations in the equatorial regions may play a large role in generating the ring current.

Table 1. Magnetospheric spacecraft carrying ion composition and ULF wave instrumentation

A. Thermal ions (< 100 eV)

Spacecraft	Instrument Type	Dates	M/Q	Reference
OGO-1	Bennett RF	1964	1,4	Taylor et al., 1965
OGO-3	Bennett RF	1966	1,4	Taylor et al., 1970
OGO-5	Magnet	1968	1,4,16	Harris & Sharp, 1969
GEOS-1	RPA+ESA+CWF	1977-1979	1,2,4,8,16	Geiss et al., 1978
ISEE-1	RPA+ESA+CWF	1977-	1,2,4,8,16	Horwitz et al., 1982
SCATHA	RPA+magnet	1979	1,4,16	Reasoner et al., 1982
DE-1	RPA+magnet	1981-	1,2,4,8,14,16 28,30,32	Chappell et al., 1981 Craven et al., 1985

B. Hot ions (100 eV - 30 keV)

Spacecraft	Instrument Type	Dates	M/Q	Reference
1969-25B	SWF+ESA	1969	1,4,16	Sharp et al., 1974
1971-92A	SWF+ESA	1971	1,2,4,16	Shelley et al., 1972
S3-3	SWF+ESA	1976-	1,2,4,16	Sharp et al., 1977
GEOS-1	ESA+CWF	1977-1979	1,2,4,8,16	Balsiger et al., 1976
ISEE-1	ESA+CWF	1977-	1,2,4,8,16	Shelley et al., 1978
GEOS-2	ESA+CWF	1978-1985	1,2,4,8,16	Balsiger et al., 1976
SCATHA	SWF+ESA	1978-	1,2,4,8,16	Johnson et al., 1982
PROGNOZ 7	SWF+ESA	1978-1979	1,2,4,16	Lundin et al., 1979
DE-1	CWF+ESA	1981-	1,2,4,8,16	Shelley et al., 1981
CCE	CWF+ESA	1984	1,2,4,8,16	Shelley et al., 1985a

C. Energetic Ions (> 30 keV)

Spacecraft	Instrument Type	Dates	Z	Reference
Injun 4	SSD	1967	1,2	Krimigis & Van Allen, 1967
Injun 5	SSD	1968-1969	1,2,6-8	Van Allen et al., 1970
OV1-19	SSD	1969-1970	1,2	Blake & Paulikas, 1972
Exp. 45	SSD	1971-1974	1,2,≥4,≥9	Fritz & Williams, 1973
IMP-7	ESA+SSD	1972-1973	1,2,6-8	Fan et al., 1976
IMP-8	ESA+SSD	1973-1976	1,2,6-8	Tums et al., 1974
ATS-6	SSD	1974	1,2,6-8 >8	Fritz & Wilken, 1976
S3-2	PC+SSD	1975-1976	1,2,>4,>16	Scholer et al., 1979
ISEE-1, ISEE-3	ESA+ PC+SSD	1977-	1,2,6,7,8, 10-14,≥16	Hovestadt et al., 1978
ISEE-1	TOF+SSD	1977-	1,2,6-8,>8	Williams et al., 1978
SCATHA	SSD	1978-	1,2,6-10,≥12	Blake & Fennell, 1981
CCE	ESA+TOF+SSD	1984-	1,2,6,7,8	Gloeckler et al., 1985b
CCE	TOF+SSD	1984-	1,2,6-8	McEntire et al., 1985

D. Wave analyzers (ULF range)

Spacecraft	Instrument Type	Frequency	Reference
Hawkeye 1	Search coil	>1 Hz	Kintner & Gurnett, 1977
Exp. 45	Search coil	>1 Hz	Taylor et al., 1975
GEOS-1,2	Search coil	>.05 Hz	Perraut et al., 1978
	Electric dipole	>.05 Hz	Perraut et al., 1978
ATS-6	Fluxgate	>.05 Hz	Mauk & McPherron, 1980

S3-3	Electric dipole	>30 Hz	Kintner et al., 1978
DE-1	Search coil	>1 Hz	Shawhan et al., 1981
	Electric dipole	>1 Hz	Shawhan et al., 1981
ISEE-1,2	Search coil	>5.6 Hz	Gurnett et al., 1978
	Electric dipole	>5.6 Hz	Gurnett et al., 1978
ISEE-1,2	Fluxgate	<16 Hz	Russell, 1978

NOTE: For a comparison of wave detector sensitivities see Jones (1978)

ABBREVIATIONS: RPA: Retarding Potential Analyzer, ESA: Electrostatic Analyzer, CWF: Curved-plate Wien Filter, SSD: Solid State Detector, TOF: Time-of-flight; PC: Proportional counter.

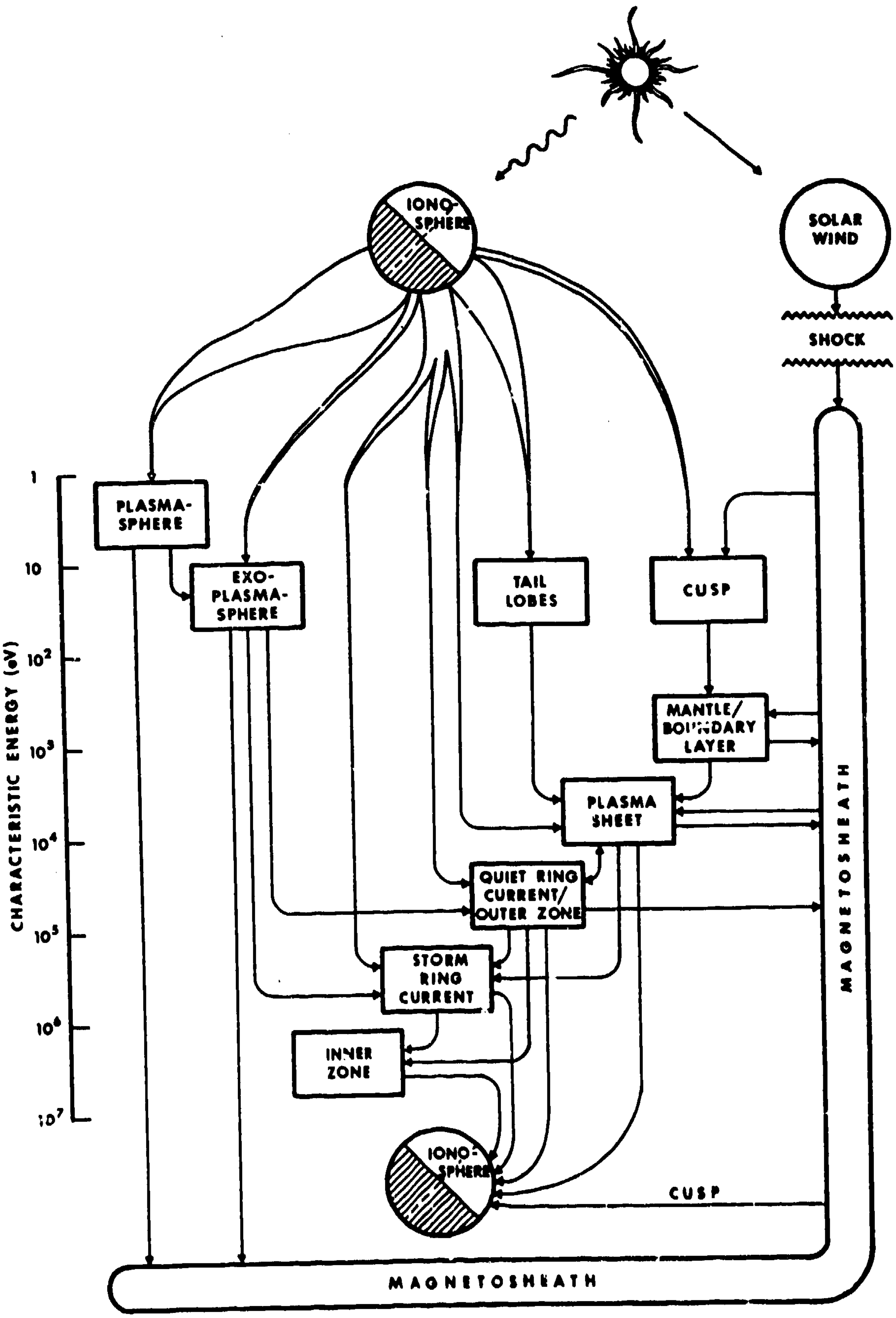
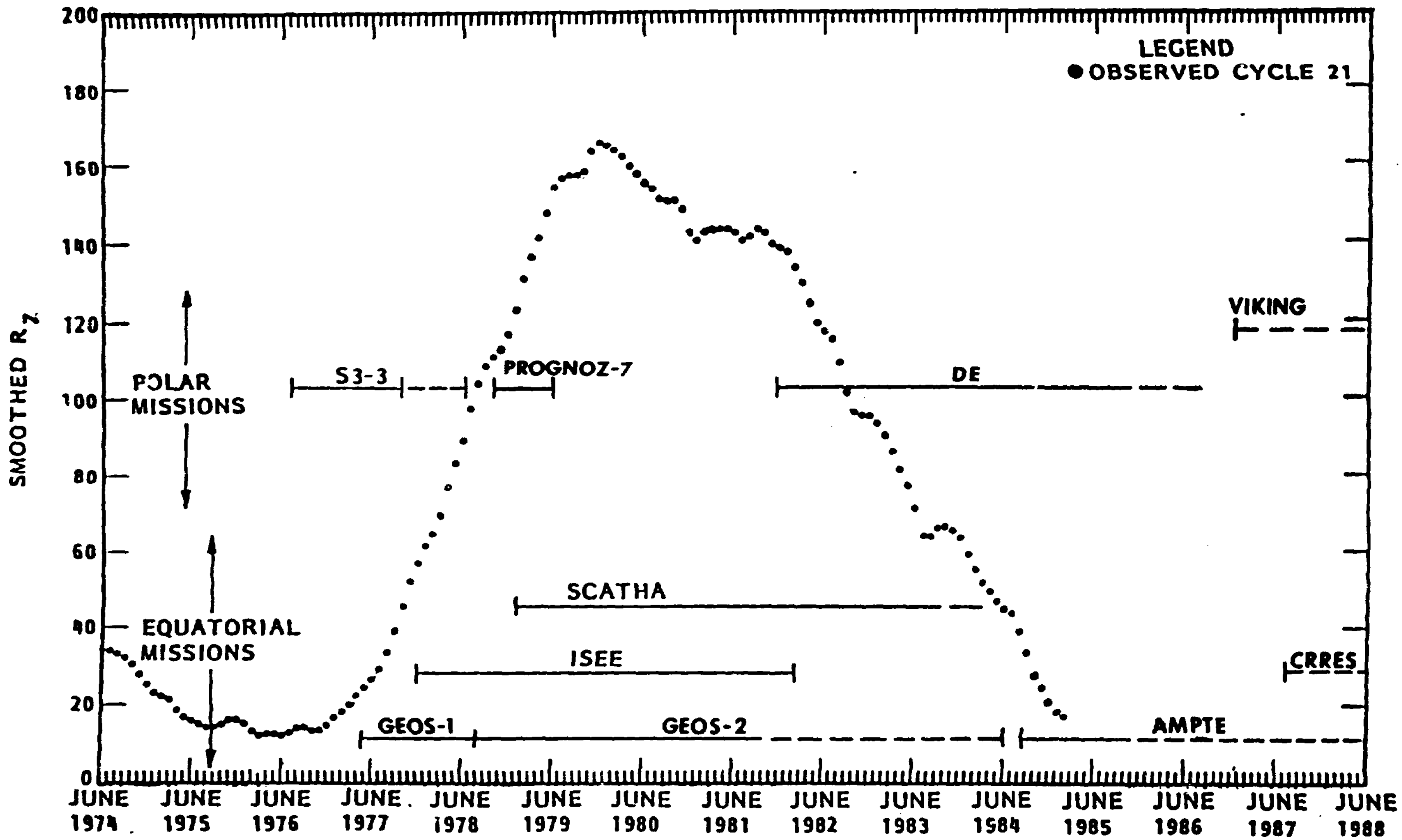
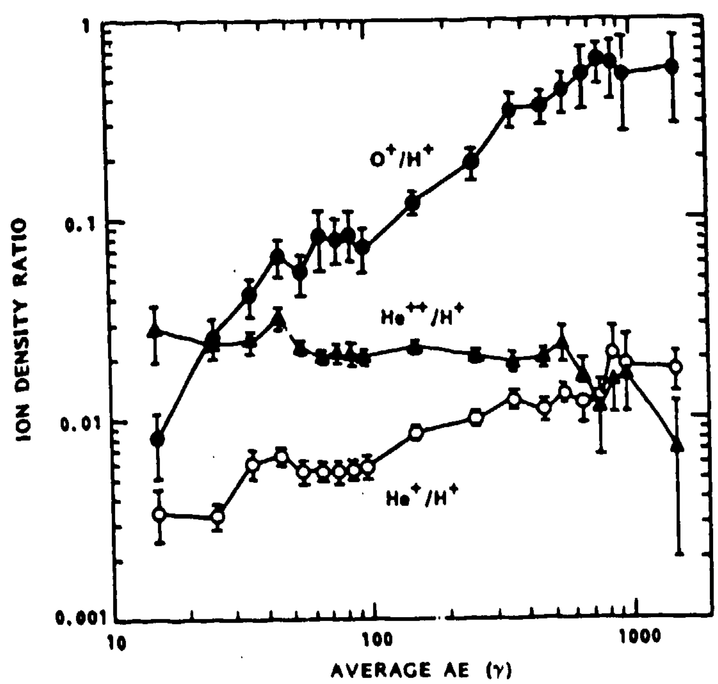

IONO-SPHERE
SOLAR WIND
SHOCK
1
10
10²
10³
10⁴
10⁵
10⁶
10⁷
CHARACTERISTIC ENERGY (eV)
PLASMA-SPHERE
EXO-PLASMA-SPHERE
TAIL LOBES
CUSP
MANTLE/ BOUNDARY LAYER
PLASMA SHEET
QUIET RING CURRENT/ OUTER ZONE
STORM RING CURRENT
INNER ZONE
IONO-SPHERE
CUSP
MAGNETOSHEATH
MAGNETOSHEATH

Figure 1.



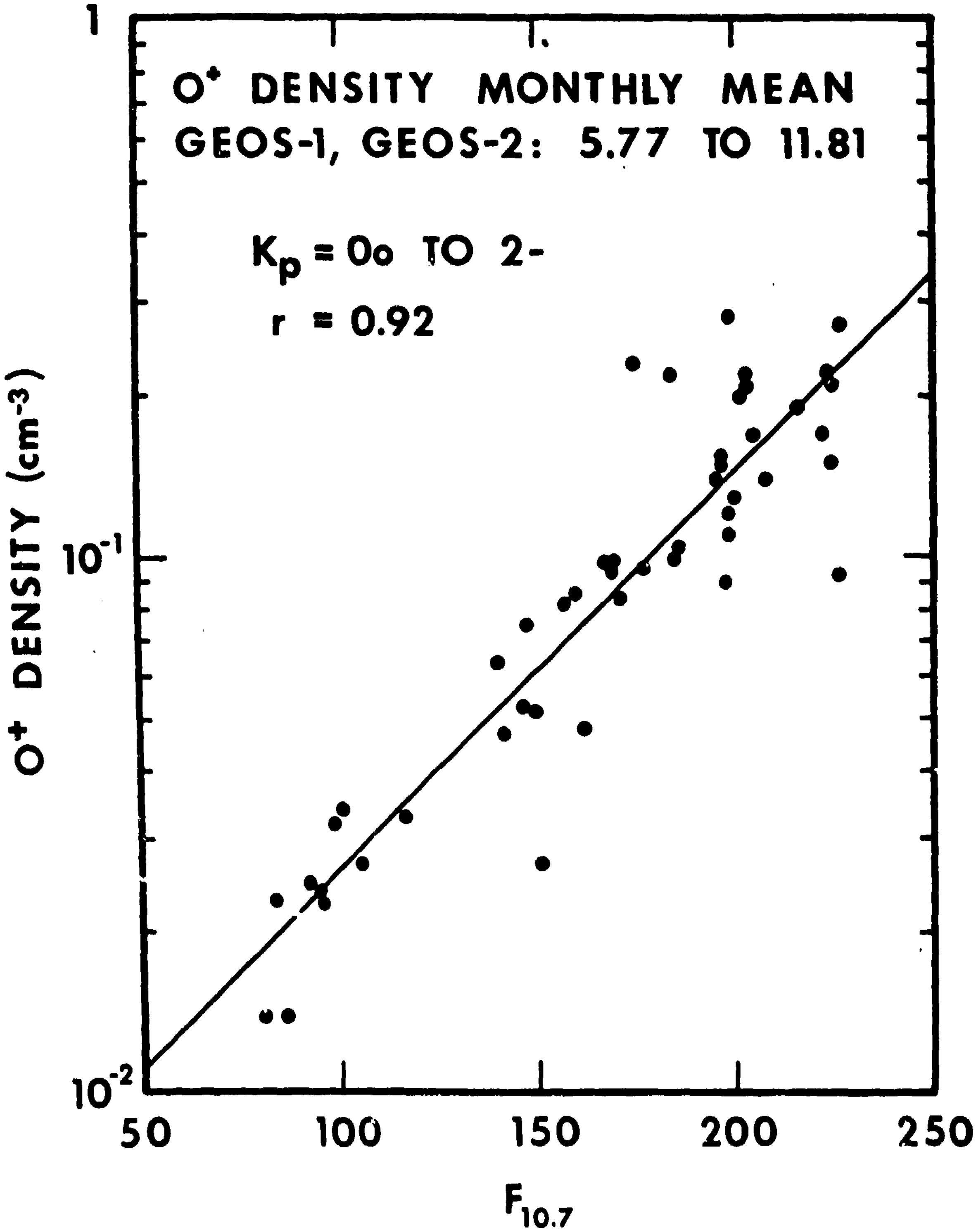
LEGEND
● OBSERVED CYCLE 21
SMOOTHED R_Z
200
180
160
140
120
100
80
60
40
20
0
POLAR MISSIONS
EQUATORIAL MISSIONS
S3-3
PROGNOZ-7
DE
VIKING
SCATHA
ISEE
CRRES
GEOS-1
GEOS-2
AMPTE
JUNE 1974
JUNE 1975
JUNE 1976
JUNE 1977
JUNE 1978
JUNE 1979
JUNE 1980
JUNE 1981
JUNE 1982
JUNE 1983
JUNE 1984
JUNE 1985
JUNE 1986
JUNE 1987
JUNE 1988

Figure 2.



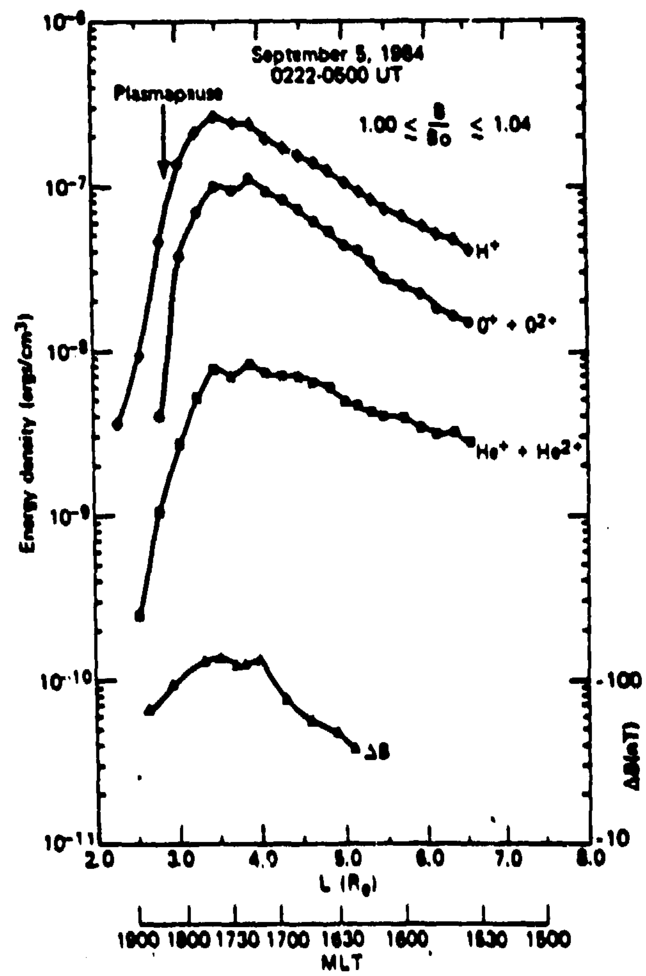
1
0.1
0.01
0.001
10
100
1000
ION DENSITY RATIO
AVERAGE AE (γ)
O+/H+
He++/H+
He+/H+

Figure 3.



O+ DENSITY MONTHLY MEAN
GEOS-1, GEOS-2: 5.77 TO 11.81
Kp = 0o TO 2-
r = 0.92
1
10-1
10-2
O+ DENSITY (cm-3)
50
100
150
200
250
F10.7

Figure 4.



September 5, 1984
0222-0600 UT
Plasmapause
$1.00 \leq \frac{B}{B_0} \leq 1.04$
H^+
$O^+ + O^{2+}$
$He^+ + He^{2+}$
ΔB
Energy density (ergs/cm^3)
ΔB(nT)
L (R_e)
MLT

Figure 5.

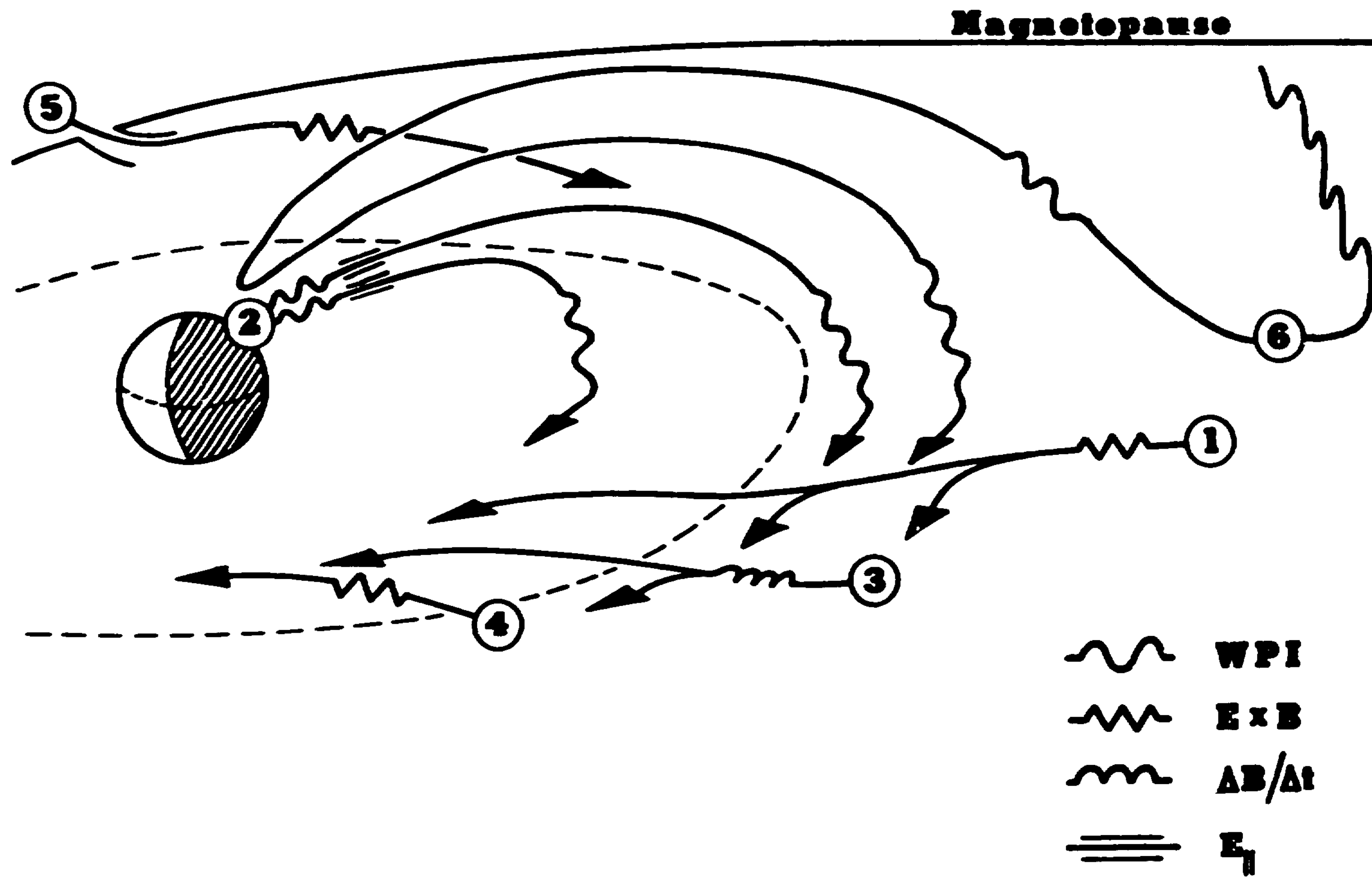


Figure 6.